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Integration of solar energy in coal-fired power plants retrofitted with carbon capture: A review

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A B S T R A C T

This paper reviews the utilization of solar thermal energy technology in assisting coal-fired power plants retrofitted with post-combustion carbon capture (PCC). The focus is on compensating the so-called 'energy penalty' imposed on the power plant output by the introduction of PCC plant operations. The integration of solar thermal energy can offset the power plant output reduction due to the PCC installation by totally, or partially providing the energy requirement of the carbon capture plant. The main process integration approaches proposed in this regard are reviewed; their advantages and drawbacks are discussed considering technical and climatic factors. The paper also discusses the merits of this hybridization of power, capture and solar plants as a transition solution for future low-carbon power generation.

Contents

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1. Introduction

Fossil fuels, in particular coal, are the most widely used energy sources due to their low prices, convenience of use and high energy density. However, conventional coal-fired power plants are the major contributors to carbon emission (78.2% from large stationary emission sources). Despite the environmental concerns, the demand for fossil-fuelled energy sector is still growing which makes it the main target for emission reduction solutions [1].

Integration of renewable energy with fossil fuel-based power production, also known as 'hybridization', can offer reduced carbon emissions due to the lower carbon intensity offered by renewable energy technologies. However, to date these renewable technologies are still under various phases of research and commercialization and are yet to be technically and economically feasible as standalone power production systems. Replacing fossil fuels by renewable energy sources is considered a long-term strategy and fossil fuels are most likely to remain the leading reliable sources of electricity generation in the short to medium terms.

Strategies such as carbon dioxide (CO_2) capture and sequestration (CCS) can offer a bridge towards the long-term scenario, one dominated by renewables energy generation. In other words, CCS can serve as a transient step towards low emission energy generation, albeit within a currently narrow envelope of incentives-driven economic feasibility. Therefore, fossil-fuel fired power plants, with their challenging goals of reliability and affordability of supply, can continue to operate while meeting their greenhouse gas (GHGs) emissions targets through retrofitting of CCS while implementing a stepwise strategy of renewables integration [2,3].

Currently, several approaches are available for carbon capture technology, which are described in detail in Ref. [4]. These technologies include pre-combustion, oxyfuel combustion and post-combustion carbon capture. Among these technologies, solvent-based absorption-stripping PCC is regarded by many to be the most accessible option for existing power plants. The process is reasonably developed to be retrofitted with existing power plants [5–7].

Despite its potential environmental benefits, integration of PCC technology in the power plant leads to considerable energy penalty and significant loss in power plant output ranging from 19.5% to 40% of the original output of conventional power plants [1,8,9]. This penalty is due to two main energy loads required for PCC operation that are parasitically supplied by the power plant. The first load is the energy required for solvent regeneration at the PCC stripping column reboiler which is typically supplied by steam bled from the power plant low pressure turbine. The extracted steam has higher temperature than that of required for solvent regeneration and could otherwise be used to produce electricity. The second load on the power plant is a considerable amount of power required for operation of the PCC auxiliary systems such as pumps and CO_2 compression line(s) leading to additional energy penalty. The resulted notable total penalty in power plant output (total penalty resulted from diverted supply of thermal energy to reboiler and PCC auxiliary loads) creates operational and economic uncertainties for power generation sectors about the viability of the PCC retrofitting of conventional power plants.

Several solutions have been investigated globally to reduce this energy penalty. These efforts have been mainly concentrated on process improvement solutions such as absorber/stripper parameter optimization, modification to the CO_2 scrubbing process and power plant heat integration. However, such strategies provide limited improvements to the system energy penalty [10].

Solar thermal energy can be effectively used to compensate the power plant energy penalty resulted from PCC installation. A solar thermal energy plant can be integrated (hybridized) in PCC-retrofitted power plant in either electricity and/or steam (heat) production modes. The solar installation could be designed to maintain the power plant original power output or a certain level of improvement (reduction) in the power plant output penalty resulted from PCC operation.

A PCC plant has significant compatibility with a solar thermal plant (or with renewable energy plants in general). Due to the possibility of the PCC potentially acting as a flexible load to cover intermittency of the solar radiation to meet the peak demand periods more flexibly [11].

The concept is relatively new and there is limited number of related research works available in the literature. This review focuses on the potential of solar thermal technology to be integrated with PCC-retrofitted power plants. A detailed review outlining major concepts investigated in existing studies on such solar integration is presented, followed by a review on the current research trends in the field. Further, the features and capability of different solar thermal energy technologies to be integrated with PCC retrofitted power plant are reviewed, along with an overview of the global profile of standalone solar thermal power generation.

2. Conventional solvent-based post-combustion carbon capture technology

A simplified diagram of the standard amine based (MEA) PCC system is shown in Fig. 1. The flue gas stream from the power

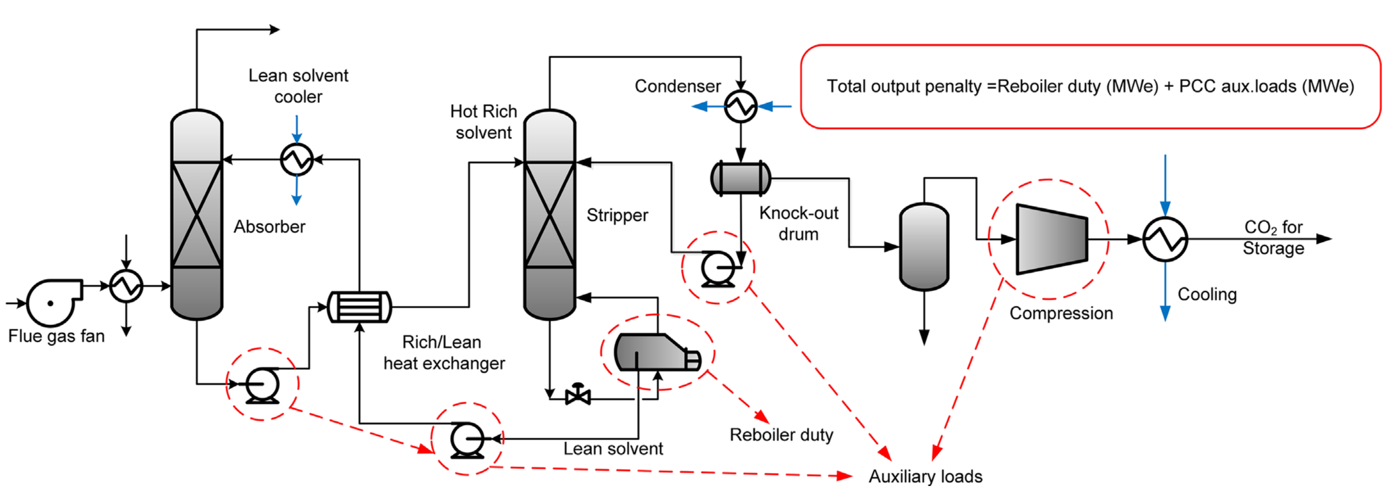

Fig. 1. Process flow diagram of conventional PCC plant.

plant passes through a cooler at a temperature of 40–60 °C and soot and impurities are removed [12]. Then, it enters the absorber, which is a packed/tray column in which, it chemically reacts with solvent in counter-current flow. Carbon dioxide and solvent form a chemically loose bond compound. The rich stream flows through a heat exchanger prior to entering the stripper. In the stripper, the chemical reaction is reversed using thermal energy. The thermal energy required for this reverse reaction is provided in a reboiler. The stripper exchanges the heat between steam and solvent (regeneration temperature requirements is in the range of 100–140 °C) [6,9,12]. Almost pure CO_2 is compressed in compression train(s) for transport and storage and lean solvent is recycled back to the absorber vessel to repeat the cycle. In conventional PCC-retrofitted power plants, the thermal energy for solvent regeneration is parasitically provided by steam extracted from low-pressure side of turbine circuit resulting in considerable energy penalty and consequently power plant output loss. Another parasitic load on power plant is the power requirement for PCC auxiliary systems operation. The steam required for CO_2 capture varies depending on the design of the PCC system, the base and operational load of power plant, carbon capture rate, heat integration, optimization of operating conditions of PCC and process configuration or operating scheme in the stripping section [11].

3. Integration of solar thermal energy in PCC-retrofitted power plants: a step towards low-carbon energy generation

In the literature, several approaches were investigated to improve the power plant output penalty by means of integration of solar thermal energy with PCC and/or power plant. The studied ideas include partially or totally compensating of PCC reboiler duty by solar thermal energy [11,13,14] and power plant repowering through solar thermal application in plant feed water preheating or parallel steam generation [15,16].

It should be noted that in addition to the power plant output penalty resulted from the thermal energy required for PCC solvent regeneration, a considerable amount of electrical load is required for PCC auxiliary systems (CO_2 compression, pumps, etc.) which is conventionally provided by power plant. Such additional parasitic load is often overlooked in the existing literature and there is almost no particular integration configuration proposed to provide a solution to compensate both penalties (solvent regeneration and PCC auxiliary power loads).

Solar-assisted PCC system features very attractive potentials: the steam conditions could be designed to feasibly meet the stripping requirements. In addition, as the option of using steam bleed from the turbine circuit is always available; the fraction of solar energy to be used can be optimized based on the availability, economic factors and demand. Some potential areas of further investigation in this field could be the additional investigation on using thermal storage system, eliminating solar steam generator and heating the solvent in reboiler directly by solar heat transfer fluid and direct recirculation of solvent through solar collector field. The latter option however, would require close study of two-phase flow of CO_2 and solvent in solar field which is currently under further research and investigation [11,14].

Although there is a great deal of potential in solar-assisted carbon capture and such integration looks very promising, the technology is still under early stages of evaluation and development and remains relatively immature. Therefore, currently there is no commercial installation of solar integrated power plant with PCC worldwide. In pilot scale however, Commonwealth Scientific and Industrial Research Organisation (CSIRO) is working on a very small pilot scale solar thermal reboiler. The aim is to use the solar thermal energy provided by a parabolic trough solar field to supply the reboiler duty of a CSIRO-operated carbon capture plant located at a local power station [17].

A limited number of feasibility studies and techno-economic evaluations have been carried out and are available in the literature. They try to investigate the system feasibility against key economic factors and assess the potential challenges. The next sections review the main features of each work.

3.1. Partial or total compensation of reboiler duty by solar thermal energy

Wibberley et al. [18] first patented the novel concept of integration of solar heat for reboiler duty in PCC-retrofitted power plants. In their system, numbers of different possible configurations for integration of solar energy were proposed. In their approach, the required reboiler thermal energy was provided partly or totally based on the availability by means of heated solar heat transfer fluid coming from a solar collector field. The heat transfer fluid returning to solar field was used for other services such as low-pressure side feed water preheater repowering. Compared to conventional PCC-retrofitted power plants where totals stripper reboiler steam was provided by steam bled from turbine circuit, this integration was claimed to considerably reduce the penalty in the power plant output.

The solar thermal storage was provided by the selective accumulation of the CO_2 enriched or regenerated solvent in one or two storage vessels. The dispatch of lean and reach solvent stored was decided based on carbon capture rate required and operation demand. The proposed storage alternative is very promising to reduce the cost of solar installation. In order to guarantee the availability of the solar heat for the CO_2 capture process in case of unavailability or insufficiency of solar thermal energy, steam extraction lines from the turbine circuit were remained in place to be used as well.

3.2. Total supply of reboiler duty using mid to high temperature/efficiency solar collector systems

Cohen et al. [11] performed a preliminary feasibility study based on a very roughly estimated size and cost of a nominal solar-assisted carbon capture plant. They compared the cost of PCC operation using either solar produced steam or turbine-bled steam to investigate power plant economics in the context of electricity dispatch. Their base case for the study was a 500 MW gross output coal-fired power plant retrofitted with 30% MEA PCC system. Investigating different concentrating solar thermal technologies, they proposed the use of mid temperature/efficiency collectors, particularly the parabolic trough solar collector system (PTC) (Section 6.2) in virtue of its technology maturity and reasonably low cost. They assumed that based on the operating condition of the produced steam, PTC system would be capable of providing energy requirement for PCC reboiler duty and driving a CO_2 compression train as well.

Their basis for solar field sizing was to supply the entire steam requirement for both CO_2 compression and solvent regeneration of the PCC (when receiving average direct normal irradiation (DNI) of 561 W/m^2). Two solar thermal plants were sized, one without and another with 6 h of molten salt thermal storage. The resulting aperture area (more than 2 km^2) and capital cost were considerably large particularly when the solar system was oversized for thermal storage. They compared the cost of the plant under four operating conditions and calculated the cost of electrical output compensated by solar integration of the PCC plant.

They concluded that it would be less feasible to use high quality solar energy in carbon capture to regain plant output rather than simply using high temperature, high efficiency solar steam for

direct electricity generation. Beside their formerly stated recommendation, they also suggested that low temperature/efficiency solar technologies might have better integration potential with carbon capture compared to mid to high efficiency collector technologies. In addition, they proposed that a minimum electricity price in the order of \$100/MW h could offset the cost of solar installation, which could be achievable with substantial CO_2 prices, but again solar heat availability and thermal storage would be potential barriers. They also suggested that a more realistic approach might be using solar energy to provide a fraction of the reboiler duty requirement.

3.3. Supply of reboiler duty by solar steam and/or turbine circuit steam

Mokhtar et al. [13] investigated a super structure comprising of a solar-integrated 30% MEA PCC plant retrofitted to a 300 MW power plant in New South Wales, Australia. They used an economic cost model to assess the net benefit of such an integration compared to a conventional PCC-retrofitted power plant (Fig. 2).

They argued that using solar system to supply 100% of the reboiler thermal energy would be considerably expensive and would only be possible if a very large thermal storage system was used to guarantee the availability of solar energy for most of the operation time. Therefore, partial supply of reboiler duty from solar thermal energy would be more feasible. In addition, keeping in view the temperature range of steam needed for reboiler, low temperature and efficiency solar collectors might more efficiently provide the quality of steam required for solvent regeneration. This would allow the better quality steam bled from the turbine to be utilized in electricity generation and consequently the power plant output penalty could improve, i.e. be reduced.

They performed a feasibility study to assess the combination of regional and climatic variables such as available solar radiation, carbon price, fuel price, fuel carbon intensity, and post-capture costs on the feasibility of the solar assisted PCC system. For this purpose, they prepared a costing model presenting net revenue of the project against the solar fraction. The share of solar thermal energy in reboiler duty supply on the other hand, depended on the solar field size and thermal storage size. They carried out a techno-economic analysis to investigate the different combination of parameters to determine the sizes of solar field and storage. The proposed solar thermal collector technology was mid temperature/efficiency linear fresnel reflectors (LFR) (Section 6.2). The LFR technology system has very similar performance but the benefit of lower cost compared to the state of the art PTC technology.

Their proposed control system for solar supply of the reboiler heat duty is an ON/OFF scheme. In this case, solar thermal energy is provided from solar collector field and/or thermal storage if the available amount is equal to regeneration energy required in the reboiler. If the combined energy is not enough, the total amount of energy will be provided by steam bled from the turbine circuit. This system is not optimized in regards to utilization of solar plant in the superstructure operation, as; the solar thermal energy is not effectively used when it is partially available. The authors acknowledged this issue and suggested that this system could be optimized and led to higher engagement of the solar field if more advanced control philosophy was applied.

Authors considered a wide price ranges for solar collector technology (\$100–\$600/m^2) and carbon pricing (\$0–\$200/tonne)

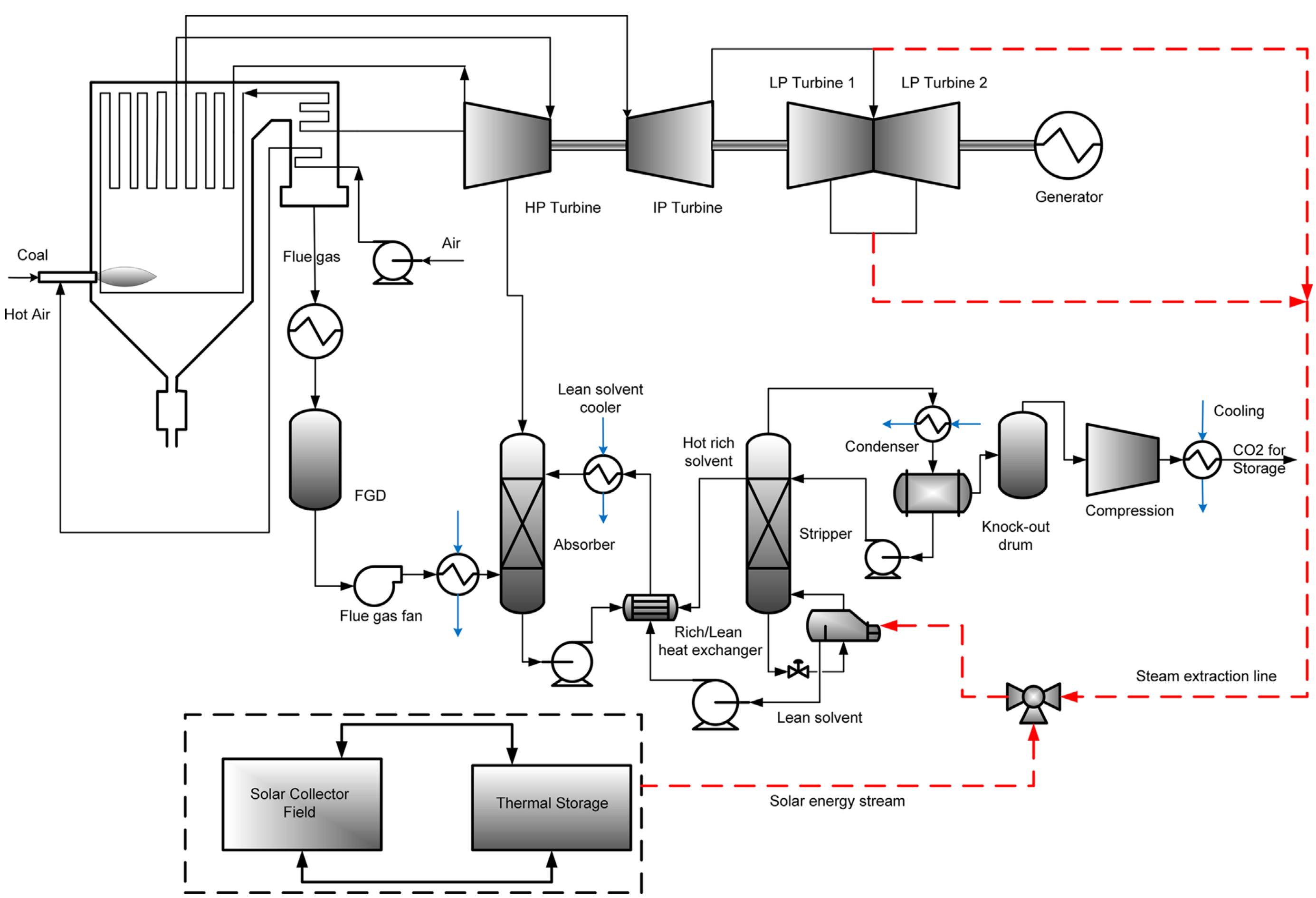

Fig. 2. Process flow diagram of solar-assisted PCC (solar thermal energy used for the reboiler duty) [13].

in their analysis. They also stated that based on the conditions in NSW Australia, the system would become feasible only, if very low cost solar thermal collectors were used. Their results showed that at current electricity prices, a system of solar collectors of $100/m^2 and solar load fraction of 22% (the fraction of solvent regeneration heat duty to be provided by solar thermal energy) and carbon price of $100/tonne could be economically feasible. They also stated that this technology would take cost advantage at higher carbon and electricity prices. Also higher net power plant and carbon capture efficiency would increase the feasibility of the plant.

3.4. Effects of location and incentives on solar-assisted PCC technology (Australia)

Qadir et al. [19] techno-economically analysed a coal-fired power plant retrofitted with MEA-based PCC, partly assisted with solar thermal technology. The superstructure investigated in their work comprised of a heat integrated 660 MW coal fired power plant retrofitted with MEA solvent PCC plant and a solar collector field.

Three locations in Australia were investigated: Sydney, Townsville and Melbourne. The rationale for this was to find the best potential area to implement such a project as several coal-fired power stations were located in these three locations and the potential of solar radiation was relatively promising.

In their assessment, they investigated the economic performance of the base case of PCC-retrofitted power plant when the PCC was retrofitted with different types of low temperature/low efficiency solar collectors (Section 6.1) or mid temperature/efficiency solar collectors (Section 6.2). Each assessment was performed for the three locations selected. Further, they divided the base case in two scenarios; when base case subsystems had heat integration through the use of preliminary Heat Exchanger Networks (HENs) [20] against the system without any heat integration between subsystems, assuming that adding the solar thermal technology, would not change the power plant efficiency stated in Khalilpour and Abbas [20] HEN model.

They concluded that evacuated tube solar collector (ETC) technology (Section 6.1) would be the most promising option amongst solar collectors when the three subsystems (solar plant, PCC and power plant) had heat integration while PTC performed best in the case with no heat integration.

For further economic investigation, the authors considered the heat-integrated plant with ETC as the base case in virtue of its consistent higher net annual benefit and good performance. The constantly negative net annual benefit showed that without incentives, the solar-assisted carbon capture would not be feasible to be deployed in any of the three locations selected for the investigation.

To assess the effect of incentives on the economic viability of the super structure, the authors introduced three potential incentives that the system could be granted; renewable energy certificates (RECs), carbon tax/credits and government subsidies (grants) which were taken into account revising Mokhtar et al. [13] economic model.

Firstly, they assumed that solar thermal assisted PCC could be eligible for Australian government subsidies through Renewable Energy Development Program (REDP), ranging from $2 to $30 million depending on the fraction of solar energy (solar share) used in the process. They showed that the plant subsidizing improved the net annual benefits in all locations and the improvement rate increased in higher solar fractions. However, this measure was not enough to provide positive net annual benefits in any location.

To investigate the effects of carbon tax/credits, they introduced four carbon price scenarios using an average carbon tax over the 25-year life of the plant. The improvement effect of first scenario was found to be insignificant compared to the rest of scenarios, which all provided positive net annual benefits in Sydney and Townsville at a solar fraction close to 0.20.

Another potential incentive was renewable energy certificate (REC) scheme that issues forms of market-traded credits large-scale generation certificates (LGCs) or small-scale technology certificates (STCs) for every MWh of electricity either produced or displaced using renewable technologies. Authors stated that currently no RECs are granted to solar-assisted PCC in the Australian context, as the solar thermal energy is used for heat production rather than power production. However, an investigation aiming to outline the positive effects of such grants on the viability of solar assisted PCC would encourage the decision making authorities to allow LGCs to be granted to these plants like other renewable technologies.

In this investigation, they assumed that LGC price would be linearly related to carbon price. They compared the net benefit of system with and without RECs for four carbon taxes. They showed that addition of the LGCs would considerably improve the net annual benefit of the project resulting in positive net annual benefit in all three locations. Also a high solar load fraction of around 0.8 was economically achievable at highest carbon price in Townsville. They concluded that solar assisted PCC concept was very location and climatic sensitive and factors like spot electricity prices and location would considerably determine its viability. They proposed the best location for the solar-assisted carbon capture plant in Australia to be Townsville due to its higher ambient temperature and highest solar radiation.

3.5. Effects of climatic factors on solar-assisted PCC technology (global locations)

Li et al. [10] performed a techno-economic feasibility study for solar-assisted PCC plants in three different locations around the world to evaluate the effects of climatic conditions, solar thermal technology type and the ratio of CO_2 recovery. Unlike Mokhtar's [13] and Qadir's [19] costing models which are based on the net annual revenue, their economic model evaluates the electricity costs, cost of CO_2 avoidance and capital required for solar-assisted PCC system. Their selected locations were Alice Springs in Australia, Beijing in China, and Denver in United States. Two types of solar thermal collector technologies that were investigated in this study were PTC and ETC. The authors evaluated the effects of the solar collector price, thermal storage price (The selected storage media was phase change material) and carbon dioxide recovery ratio on the economic feasibility of the plant.

Similar to other existing feasibility studies in this field, they concluded that for solar-assisted PCC process, the cost of electricity and cost of CO_2 avoidance were climatic dependent and directly related to working hours of solar thermal collectors. They stated that although the effect of implementation of a thermal storage facility on total capital cost was considerable, the enhancement achieved in utilizing the available solar energy for further use would drop the cost of electricity and CO_2 avoidance. Furthermore, they reported that cost of solar thermal collection field affected these two costs most significantly showing that cost of $90/m^2 and lower for ETC and $150/m^2 and less for PTC would economically justify the implementation of this technology. Based on their study, Alice Spring in Australia had the lowest cost of electricity, CO_2 avoidance and total capital requirement regardless of the type of solar thermal collection technology used, due to its highest insolation that resulted in smallest solar field required area.

4. Solar repowering of PCC-retrofitted power plants (solar hybridization)

Repowering of existing power plants with solar thermal energy is considered a very promising option towards increasing the share of renewable energy in power production. Retrofitting the existing power plants with solar technology allows for gradual switch to renewable energy future while continuing use of preserved well-established existing fossil-fuelled power plants. It also potentially reduces the land and environmental permitting issues that are normally involved with new standalone solar power plant installations. The solar to electricity efficiency of a solar energy fraction in a hybrid system is better than that of standalone solar power plants [21]. However, it should be noted that solar thermal installation requires large land and hence, location factors such as availability of land near the conventional power plant along with promising solar insolation level should be taken to account for a successful and feasible solar hybridization. A comprehensive review on solar repowering technology is provided in Ref. [21].

In order to repower a power plant, solar thermal energy can be integrated in power plant steam cycle in two possible ways. The first option is to preheat the feed water of the Rankine cycle, which is the most common repowering approach for existing power plants. In a conventional Rankine cycle, the feed water is preheated via a number of feed water preheaters located at the high-pressure and low-pressure sides of the steam cycle. The duty of these feed water preheaters are conventionally provided using different qualities of steam extracted from different stages of the turbine circuit. Solar repowering will substitute these steam extraction lines by solar thermal energy, which will result in elimination of parasitical preheating steam extracts from the turbine circuit. Consequently, the recovered steam will expand in turbines and produce more electricity. Technically, any of the high-pressure side or low-pressure side feed water preheaters could be repowered by solar thermal energy. Amongst the feed water preheaters of a power plant, repowering high-pressure side feed water preheaters shows the most promising performance and will result in higher solar electricity production with lower capital cost requirement for solar installation [22].

Another repowering possibility is parallel steam generation in which solar steam is superheated using high- temperature high-pressure solar collectors and then directly injected to the turbine circuit or boiler of a fossil-fuelled power plant, which results in more electricity generation from constant amount of fossil fuel. This option requires high performing solar technologies and hence higher capital installation costs. Therefore, such technologies may be more feasible if used for direct power production parallel to fossil fuel power production rather than compensating the penalty of a PCC-retrofitted power plant. This repowering option is not in the scope of this review.

The idea of solar repowering of feed water preheaters to compensate the power penalty of a PCC-retrofitted power plant is relatively new. Zhao et al. [16] preliminarily assessed a system comprising of a typical 600 MW coal fired plant with PCC in China with 30% MEA PCC and 80% CO_2 capture rate, in which the high-pressure side feed water preheaters were repowered by solar energy. They assessed the solar integrated system to evaluate its positive impact on assisting carbon capture process and reducing the cost of solar installation compared to solar assisted-PCC concept. The location (Shizuishan city) was chosen due to its highest solar insolation in China. Their proposed hybridization consisted of a PCC-retrofitted power plant and a solar collection field. Parabolic trough collectors were used to collect solar heat with outlet temperature around 300 °C. The solar heat was used in an oil–water heat exchanger to heat the feed water coming from the deaerator to reach the inlet temperature of the boiler. Therefore, solar heat replaced the high-quality steam extraction lines from turbine circuit of the Rankine cycle and recovered steam would produce extra electricity and increase the power plant output. They calculated the amount of high pressure and temperature steam recovered by solar repowering and compared the extra electricity produced by it to the penalty resulted from low pressure and temperature steams used for carbon capture reboiler. Though not providing clear and detailed information about the basis of their analysis, they calculated that a smaller amount of high-pressure steam extraction recovered by repowering could create enough electricity in turbine to offset the total penalty resulted from larger amount of low-pressure steam that was used for solvent regeneration.

Their proposed operation and control scheme is quite complex and there exists a great deal of uncertainty about its practicality for existing power plants. In this scheme, no thermal storage or auxiliary heating is considered. If the solar heat is not enough to heat the total flow of feed water up to required temperature, the feed water coming from the deaerator will be divided in two streams. One stream passes through the original power plant high-pressure side feed water preheaters while the rest of feed water is heated by the solar field provided thermal energy. In other words, during normal operation the original feed water preheaters and solar preheater(s) will operated simultaneously. Due to the intermittent and extremely variable nature of solar thermal energy, this would result in continues change in the required flow rate of steam extraction from the turbine circuit. The capability to adapt to such rapid variations to the steam flow rate is not certain in most of the existing power plants old turbine systems. The authors further stated that large area requirements and notable capital cost of solar fields would still be the main obstacles to feasible implementation of solar-repowering of PCC-retrofitted power plants.

Repowering of the high-pressure side feed water preheaters of conventional power plants without PCC will increase the flow of steam at the downstream turbines and changes the operation conditions of the steam circuit. This will changes the thermal duty of feed water preheaters from its original value. Such changes on the operation of the steam cycle are often overlooked in most of the works existing in the field. The complexity increases when analysing the steam cycle conditions of a solar repowered PCC-retrofitted power plant. The resulted surplus of steam in the twin turbines due to repowering and reduction in steam flow rate due to extraction of steam for PCC reboiler operation make the steam cycle of the power plant operate under completely different conditions compared to its original states. The pressure change at the extraction points affects the feed water heating duties and temperature approach. Juan et al. [23] studied the effect of solar repowering on a coal-fired power plant (without PCC) under different operating modes. For the stand-alone power plant with solar repowering, they analysed the effect of solar integration on the steam cycle and found that the power boosting mode for the highest power plant gross load operation is the best in terms of efficiency. This work does give a good idea of the effect of solar repowering on power plant however; it does not consider the effects of the PCC operation as the study is on the effect of repowering on power plants without PCC installation.

Solar repowering of PCC-retrofitted power plants provides a very promising potential to overcome some of the challenges faced in cases where solar energy was used to provide PCC reboiler duty, directly. Firstly, this system offers more capability to utilize the solar thermal energy in the operation in cases where PCC is not in operation as the solar energy is still used in power plant power production. In this operation mode, the power plant will operate similar to hybridized power plants (power plant and solar plant without PCC) to facilitate the surplus energy produced from the

recovered high-pressure steam. The two possible modes of operations are power boosting and fuel saving modes. In power boosting mode, the power plant will operate producing surplus power from the same amount of fuel using the recovered high-pressure steam. In fuel saving mode, the power plant will operate on partial load operation producing lower gross power output, where heating requirement to produce a certain amount of power is partly provided by solar energy instead of coal [21,23,24].

Secondly, solar repowering of PCC-retrofitted power plants shows more promise to provide total power penalty from the reboiler duty with smaller size solar aperture requirement [16]. The duty of high-pressure side feed water preheaters at 100% operation is far less than the duty required for the reboiler at its 100% operation. Although the amount of recovered steam in solar repowering is less than the amount that recovered when reboiler duty is provided from solar thermal energy, its quality is much higher. This high quality steam will expand in high pressure turbine and the amount of extra power that is produced is potentially enough to offset the power that is lost due to steam being extracted for reboiler from the low pressure turbines. What is more, the solar repowering option has better chance of eligibility for LGC incentive as the thermal energy of the solar source is used to produce power.

5. Integration of solar thermal energy and/or solar power with PCC-retrofitted power plants

Most of the studies in the literature examine the strategies to compensate the output penalty imposed on PCC-retrofitted power plants due to the energy intensive solvent regeneration in the reboiler. The justification behind such notable interest in this area could be the fact that the magnitude of the thermal duty of the reboiler used for solvent regeneration is considerably large and success in providing such duty from the solar source would substantially improve the power plant output penalty. However, there exist some major challenges on practicality of this approach. Firstly, to provide the high amount of heat duty required for solvent regeneration, a reasonably high efficiency solar field and consequently high capital cost would be required. This challenge has made the researchers divert their focus from total compensation of the reboiler duty to provide a fraction of it by solar thermal energy in order to reduce the capital cost requirement [13].

Beside the output penalty resulted from solvent regeneration (around 540 MW_{th} for a 660 MW power plant with 90% capture rate), there exist a remarkable additional parasitical power load required for PCC auxiliary systems (CO_2 compression, pumps etc.). provided by the power plant (about 56 MW_e for a 660 MW power plant with 90% capture rate). Although it has a notable share in the total power plant output penalty from PCC operation, in almost all the literature studies, the amount of power required for PCC auxiliary systems were overlooked and there is almost no interest shown by researchers to provide a solution to compensate it from a source rather than the original power plant output.

Concentrated solar thermal technology has a very good potential to be used to provide the PCC auxiliary system electricity load as well as thermal energy required for PCC reboiler. The solar thermal plant can be used in either electricity and/or steam production forms to be integrated with PCC-retrofitted power plants. The close investigation on different possible configurations of such integration could be particularly useful for power sector to be used as a road map for future possible installation of solar integrated PCC-retrofitted power plants.

Parvareh et al. [25] proposed different configuration possibilities of such solar integration with a PCC-retrofitted power plant. The objective of this work, was maintaining the power plant original output during PCC operation, meaning that both reboiler duty and PCC auxiliary load were to be supplied from the solar thermal plant. The authors stated that the design of the solar plant to be used for this purposed would be highly depended on several factors such as solar share, capital cost requirements, carbon mitigation target, operational and technical parameters and economic factors such as electricity price, carbon tax and available incentives. The authors proposed the following integration configuration options:

1. Parallel solar power generation (independent concentrated solar thermal power production), in which a solar thermal power plant which is designed to produce a gross output equal to the total PCC operation penalty (resulted from PCC reboiler duty and auxiliary loads) would compensate the total decline in output of power plant due to PCC operation (Fig. 3).
2. Integration of solar technology in both forms of thermal energy and power with PCC, in which the power plant will continue to produce electricity and its original arrangement remains almost undisturbed, while the PCC is directly connected to a solar power plant, which supplies the heat and electricity loads required for its operation (Fig. 4).
3. Solar repowering of PCC-retrofitted power plants feed water preheaters. The basis of this configuration is very similar to that proposed by Zhao et al.'s [16]. The solar plant is used to produce solar thermal energy (not solar power) to supply the duty of high-pressure side feed water preheaters hence totally eliminate the use of high quality steam extract lines from the power plant turbine circuit. The authors proposed to supply total duty of preheaters from solar plant by means of a combination of solar thermal storage system and auxiliary

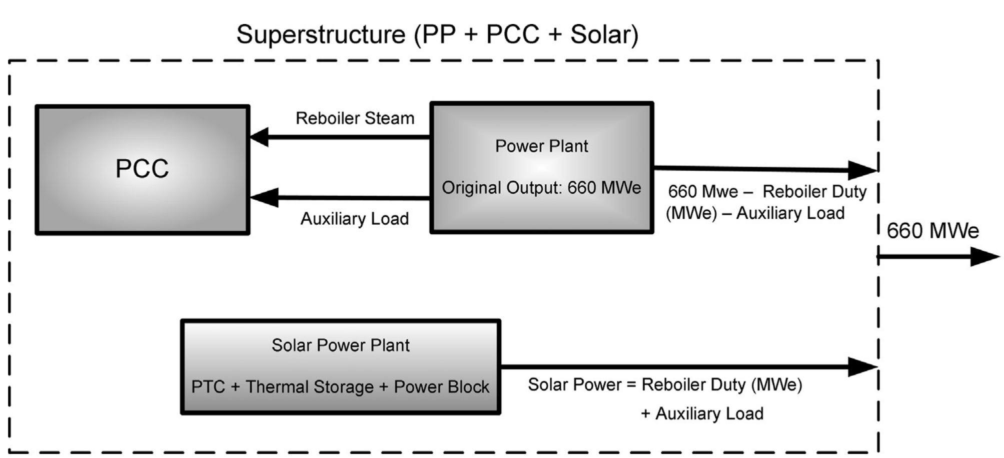

Fig. 3. Parallel solar power production.

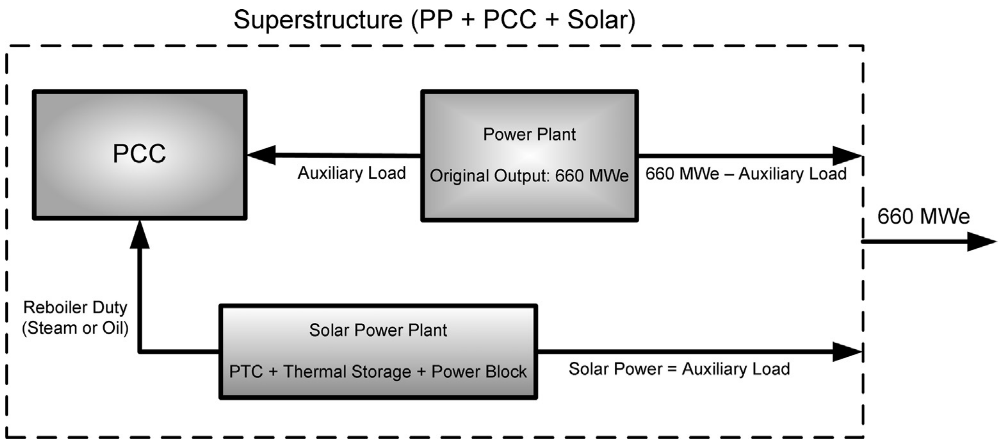

Fig. 4. Solar thermal power plant used for power and thermal energy production.

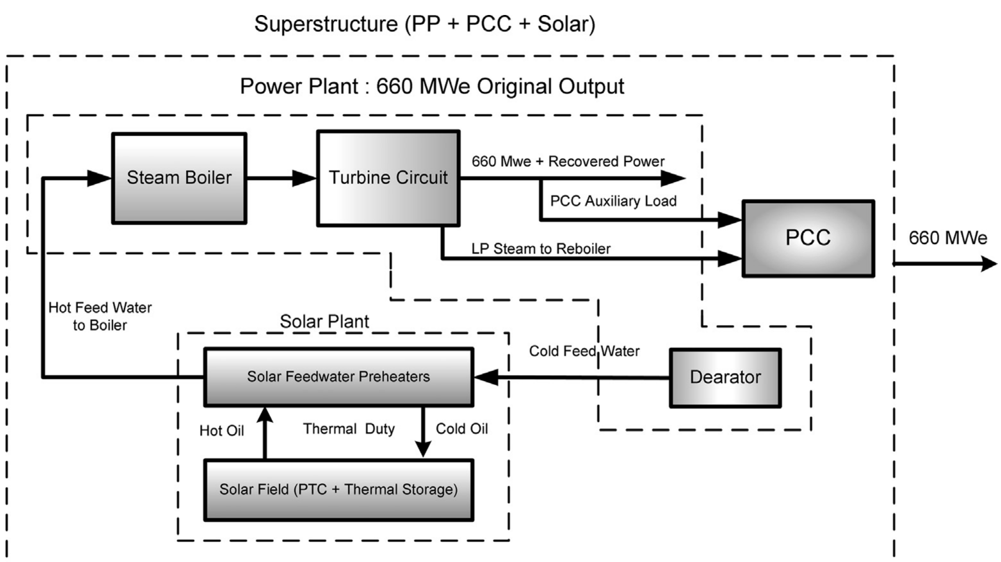

Fig. 5. Solar repowering of power plant high-pressure side feed water preheaters.

heating to overcome the operation complexity of Zhao et al.'s proposed configuration (Fig. 5).

4. Installation of a solar power and thermal energy production plant to be integrated in PCC-retrofitted power plant. In this option, the solar power plant is designed to produce the gross output equal to the load required for PCC auxiliary loads. The low quality steam bled from the original power plant turbine circuit is used to supply the reboiler duty of the PCC plant. To compensate the resulted penalty from the steam extraction, the high-pressure side feed water preheaters of the power plant are repowered by solar steam available in the solar power plant (Fig. 6).

The authors further mentioned that each of the proposed options would require to be investigated in regards to possible operational complexity, the size of solar thermal and/or power plant installation, the eligibility of each configuration for potential incentives and their compatibility for future scale up of the solar share. Table 1 summarizes their proposed configuration options.

6. Solar thermal technologies

During the last 50 years, the very fast development in solar technology has been mainly focusing on enhancement and optimization of high performance solar collectors for electricity and thermal energy production [26,27]. Due to intermittent nature of solar energy, thermal storage systems have received as much research interest as, they provide the means of storing the available solar energy and scheduling its dispatch based on economic factors and electricity and/or thermal energy demands. There is a very promising growth in research aiming to enhance different specifications of storage media along with proposing alternative storage solutions to lower the cost of thermal storage systems [28,29].

In assessment of potential of each solar collector technology to be used for solar integration of power plants with carbon capture, some key factors should be taken to account. As the energy requirement in a commercial scale PCC-retrofitted power plant is very large, the most important design parameter would be the solar area required to provide such amount of energy, which directly dominates the capital cost. Low cost solar collector technologies usually do not have high efficiency. Therefore, if used to provide the duty required for PCC reboiler duty, an extra-large solar field may be required. This will consequently result in intensive operational costs and difficulties with environmental impact and land permitting as well as considerable capital cost requirement for the installation. In order to have a more economically viable installation, these remarkable costs are required to be outweighed by the benefits gained by such solar integration.

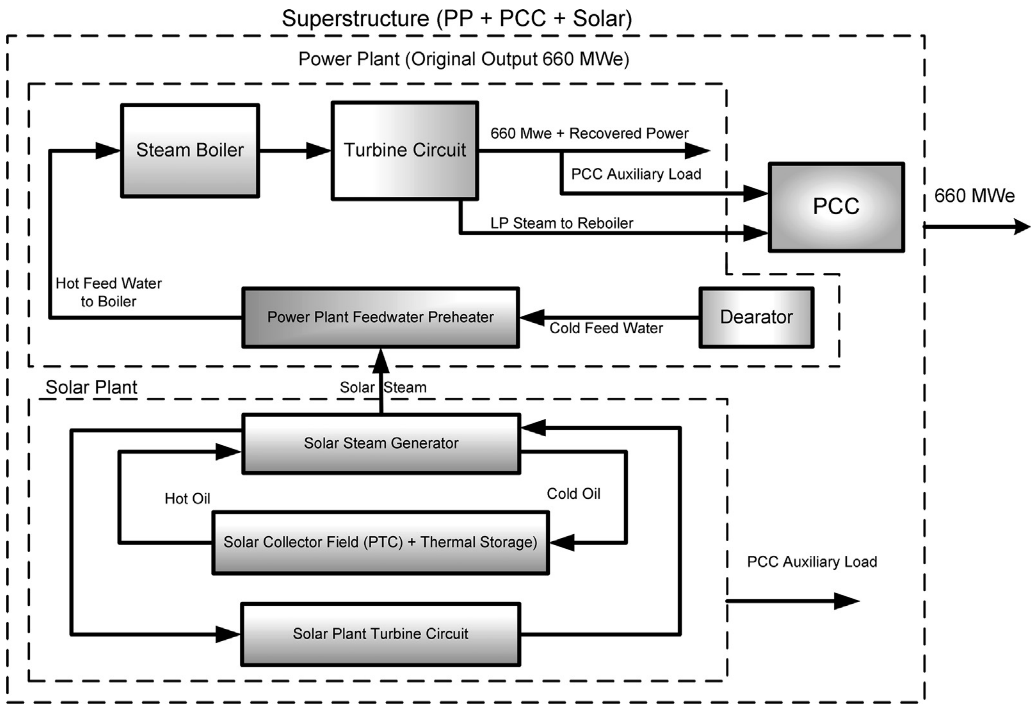

Fig. 6. Solar thermal power plant used for auxiliary loads, solar steam for feed water preheating.

Table 1
Integration of solar thermal energy and/or solar power in PCC-retrofitted power plants.

Integration option	Remarks
Parallel solar power production	A solar power plant is designed to produce power in parallel to the PCC-retrofitted fossil power plant, with gross output equal to the power plant output penalty due to PCC operation (PCC reboiler duty in MW_e+PCC auxiliary systems load). The produced solar power would compensate the total amount of PCC- retrofitted power plant output penalty
Solar plant used for power and thermal energy production	A solarthermal and power production plant is connected to PCC plant while fossil power plant operates undisturbed by PCC or solar plants operation. The solar thermal and power production plant is sized to produce electricity equal to the PCC auxiliary load. Solar heat transfer fluid or any available suitable steam qualities in solar plant could be used to provide the reboiler duty
Solar repowering (solar feed water preheating)	A solar Filed (PTC field+thermal storage and/or auxiliary system) is used for solar repowering of high and/or low pressure side feed water preheaters. The hot solar heat transfer fluid is used for high and/or low pressure feed water preheating
Solar repowering and solar power production (solar steam used for high-pressure side feed water preheaters, solar power for auxiliary loads)	A solar thermal and power production plant is used to produce power and thermal energy parallel to the power plant. The solar plant is sized to produce electricity equal to the PCC auxiliary load as well as the steam with required specification to be used for repowering of high pressure side feed water preheaters

In this section, two main solar collector categories of concentrating and non-concentrating are briefly reviewed in regards to their technology basis and their suitability to be integrated in PCC-retrofitted power plants, followed by a review on available thermal storage technologies and an overview of the current global solar thermal power installations.

6.1. Non-concentrating solar collectors

Solar thermal collectors that do not concentrate or mildly concentrate the solar irradiation are in this category. The temperature and efficiency of these collectors are relatively low. Therefore, they are less costly compared to concentrating solar collectors. Flat plate collectors (FPC) (Fig. 7), evacuated tube collectors (ETC) (Fig. 8) and compound parabolic collectors (CPC) (Fig. 9) are classified in this category.

Evacuated tube collectors (ETC) and CPC collectors seem to have good potential to be considered to be used in solar assisting power plants retrofitted with PCC. Their low construction costs and ability to heat fluids to moderate temperature ranges required for steam generation for the reboiler makes them good candidates for such solar augmentation. However, to compensate the large amount of energy required for carbon capture penalty, a large aperture area may be required. The subsequent high capital and operating costs as well as environmental impact management issues should be considered in overall investigation of practicality of their application in this technology. This type of solar technology does not meet the temperature range required for solar repowering of high-pressure side feed water preheaters.

6.2. Concentrating solar thermal collectors

Parabolic trough collector (PTC) (Fig. 10), linear Fresnel reflectors (LFR) (Fig. 11), parabolic dish reflectors (PDR) (Fig. 12) and heliostat field collectors (HFC) (Fig. 13) are classified in this category. The highest achieved temperature of concentrating solar

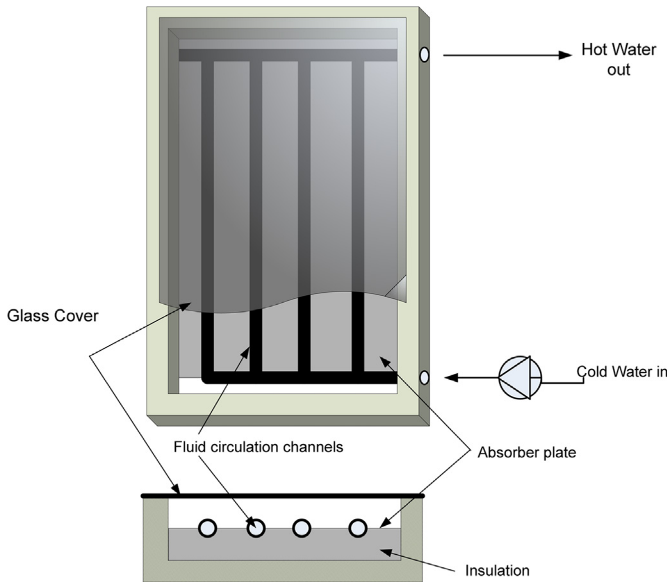

Fig. 7. Schematic of a typical FPC system.

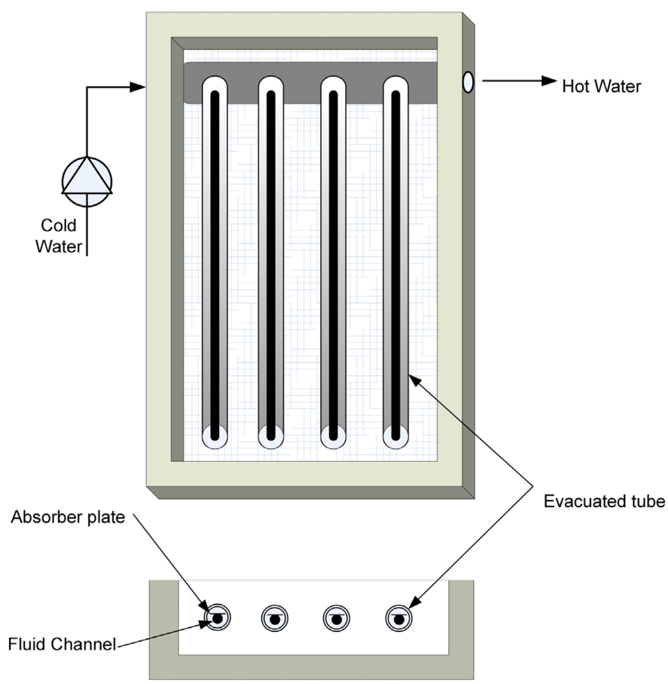

Fig. 8. Schematic of ETC system.

collectors are generally higher than the temperature range required for PCC reboiler, but they conveniently meet the temperature range required for feed water preheating in solar repowering. In addition, the high efficiency of concentrating solar collectors makes them potentially more suitable for solar integration compared to non-concentrating solar technologies as, the corresponding required solar field area either for reboiler duty or for repowering would be smaller.

Among concentrating solar technologies, PTC technology is the most promising solar technology to be used in hybridization with power plants with or without PCC system, in virtue of its mid-range temperature and relatively high efficiency along with its technology maturity and reasonable price. The technology is the most mature solar collector technology at the moment and has been commercialized and been successfully used in the industry since 1980s [30]. LFR technology is currently under investigation [31] and is predicted to have great potential to compete with PTC in integration in power plants retrofitted with PCC process due to its lower price compared to PTC technology. As parabolic dish technology is not mature and still under development, there may exist cost uncertainty and reliability issues [11] that make it unsuitable to be used with carbon capture technology. The significantly high-efficiency and high-temperature HFC technology is an excellent option to be efficiently used in standalone solar power production or power plant repowering (parallel steam production) than to be integrated in PCC-retrofitted power plants to compensate the energy penalty.

Table 2 shows a summary of the temperature range of different collectors and the type of collectors suited for different applications. A detailed review and description of various applications of solar thermal collectors in domestic and industrial sectors is provided in Ref. [26].

6.3. Thermal energy storage

There is a great deal of interest in utilization of thermal energy storage systems in solar plants. Installation of a thermal storage system increases the capacity factor as it enables the system to store the available surplus of solar energy (during daytime or periods of year with high solar insolation) for further dispatch in high demand or non-solar times. The resulting increase in system capacity factor will reduce the levelised cost of energy hence solar installation would become more economically justified. In addition, thermal storage will serve as a buffer to moderate the fluctuations of solar energy. The indirect thermal storage system with molten salt as the storage media is currently the most commonly used thermal storage system [32–34] in solar thermal plants due to its thermal stability, low vapour pressure, low viscosity, high thermal conductivity and non-flammability. However, molten salt low storage capacity increases the system volume and consequently the capital installation cost. Another alternative thermal storage technology is the thermocline system, which is more cost-efficient compared to the typical two-tank thermal storage. The system uses one storage tank to store both hot and cold media, which is filled with low cost solid filler such as rocks. The thermal gradient separates hot and cold fluid; the high-temperature fluid flows in and out from the top and low-temperature fluid flows in and out from the bottom of the tank. The system is currently under further development and investigation [30]. In solar-assisted PCC technology in which, solar energy is directly used in the reboiler, the application of the thermal storage has very promising potential to improve the controllability of the super structure (PCC+power plant+solar plant) operation and output dispatch. It will enhance the control of power plant and buffer the intermittencies in solar energy. However, the resulted increase in total capital cost required for such solar plant would be notable. This would be a very important key factor in overall plant viability investigation, keeping in view the large scale of reboiler duty, which results in a large thermal storage system [12,35].

One area that is currently being investigated and seems to be very promising is the storage of rich and lean solvent in two tanks and dispatching the solvent based on the demand and capture rate. Such a system has a great potential to reduce the cost of thermal storage for solar-assisted PCC system substantially.

Much published research in solar repowering field state that this technology does not require the installation of thermal storage system [15,23,34]. Their operation strategy is based on the simultaneous use of the solar thermal energy and conventional power plant steam extraction lines to provide the duty of feed water preheaters. In this case, the amount of thermal energy available from the solar field is used to provide total or partial amount of the thermal load required for high-pressure side feed

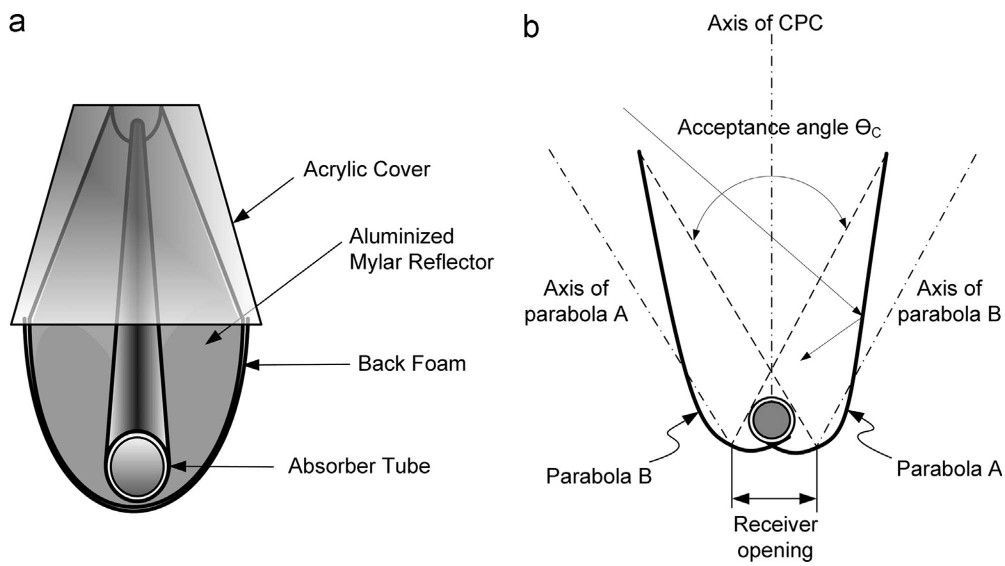

Fig. 9. Schematic of CPC system.

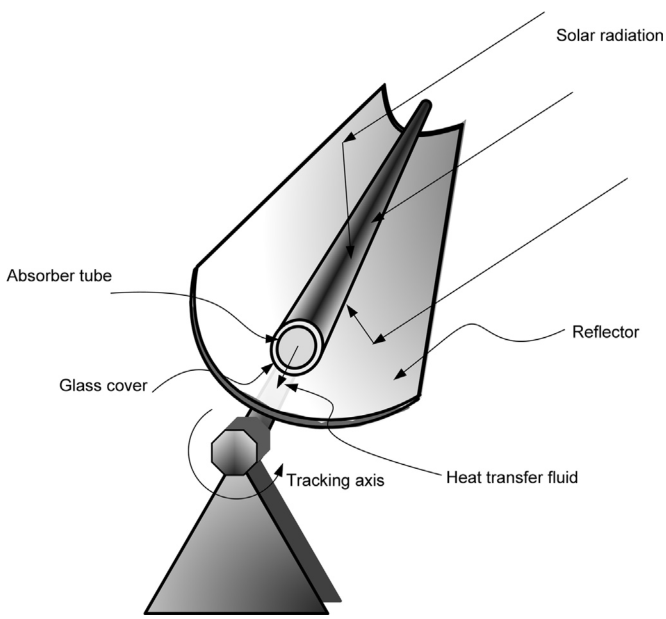

Fig. 10. Schematic of PTC system.

water preheaters. If the available solar energy is not sufficient to provide the total thermal load required, the power plant original preheaters (supplied with steam extraction lines) will be used to compensate the rest of the duty required for the high-pressure side feed water preheating. It means that the flow of feed water would be continually divided between solar preheaters and original preheaters. The ratio of the division of the feed water flow rate is based on the thermal energy available from solar field and the rest of the thermal load that should be compensated by steam extraction lines. The available thermal energy from the solar field would fluctuate very frequently as it is directly depended on meteorological conditions. Consequently, during normal operation, the flow rate of steam required to be extracted from each turbine to make up the rest of heat duty of high-pressure side feed water preheating would be changing continuously.

This operation scheme is based on the major assumption of turbine capability to adjust to frequent changes to the steam flow rate. Such assumption may be realistic for high-end technology of new turbine designs. However, for an existing power plant, it is quite uncertain. Particularly, in solar repowering of PCC-retrofitted power plants, the target power plants are mostly existing and relatively old. Therefore, thermal storage would be required to buffer the fluctuations in solar energy and eliminate the frequent variation to the steam extraction lines flow rates leading to less frequent changes to the steam flow in turbines.

Molten salts with lower solidification point temperature such as Hitec and Hitec-xl are good candidates to be used as thermal storage media for solar repowering indirect storage system. However, the considerably high cost of such storage media will amplify the existing challenge of capital cost requirement for thermal storage installation. Therefore, the size of thermal storage and solar field should be optimized based on the potential benefit that is achieved by reduction in power plant penalty.

6.4. Global installation of concentrated solar thermal power plants (CSP)

Large-scale power production plants using solar collector technology have been constructed and are in operation since 1980s [30]. The fundamental of thermal and power energy production is very similar to the conventional fossil-fuelled thermal plants. Solar energy is collected by concentrating solar collectors and either stored or directly used to produce power or solar thermal energy. The global portfolio of CSP technology installation gives a good perspective of the scale and potential of solar thermal technology in different locations worldwide. National Renewable Energy Laboratory (NREL) has provided a reasonably comprehensive list of current global concentrated solar plant projects [36].

Currently, PDRs are mostly under investigation and research and there is almost no large scale commercialized installation of these plants worldwide (except for the 1.5 MW plant in Arizona, USA) [26,27]. PTC is the most commonly used technology in CSP technology. The leading country in this type of CSP is Spain where the existing capacity of PTC plants is in the range of 1300–1500 MW and more plants each with the capacity of 100 MW are under construction [37]. Apart from Ivanpah facility in USA which is the largest HFC solar power plant under construction (400 MW) and Gemasolar power plant in Spain [37–40], most of the large scale existing and under construction CSP plants employ PTC as the solar collection technology. The world's largest existing

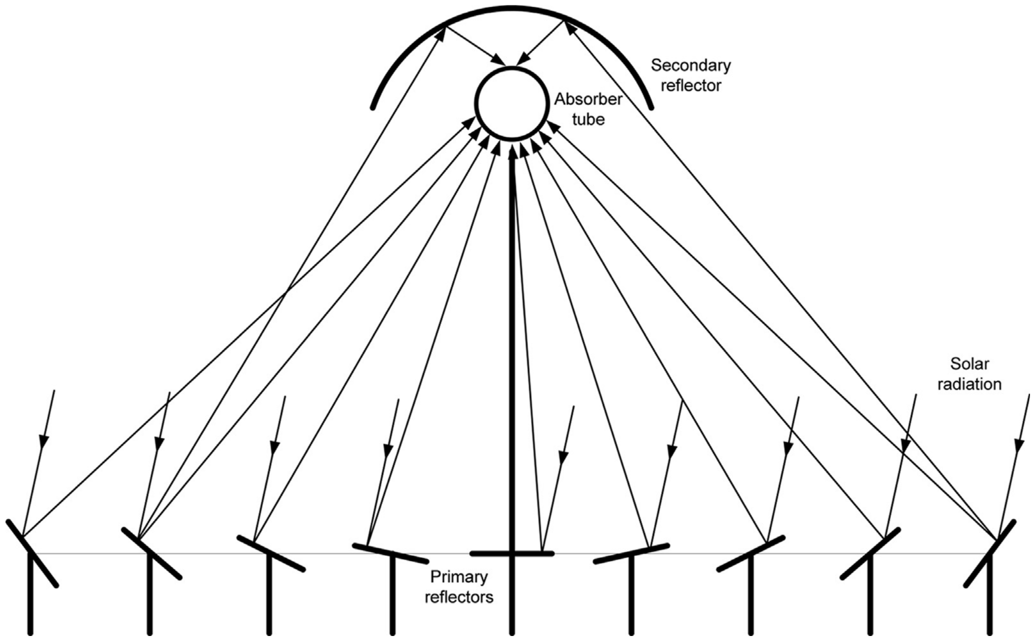

Fig. 11. Schematic of LFR system.

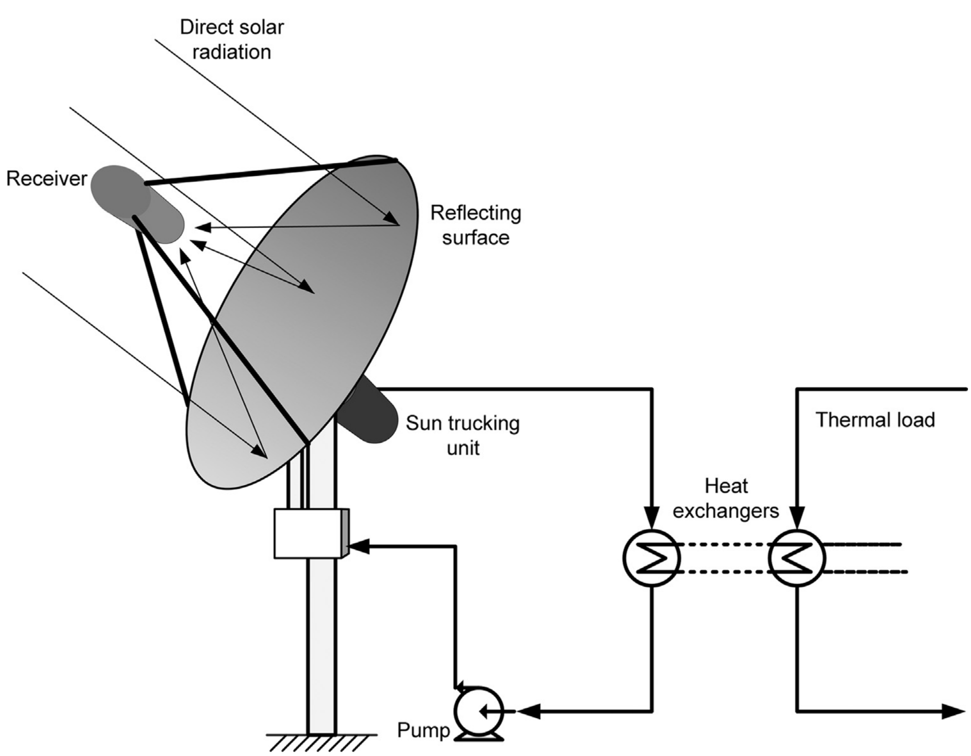

Fig. 12. Schematic of PDR system.

and under construction parabolic trough CSPs are located in California and Arizona with capacities about 354 MW and 280 MW respectively [37,41].

Compared to the PTC and HFR, the scale of the other existing CSP technologies is much smaller. The world's first commercialized HFC power plant was completed in Spain with the capacity of 17 MW [38]. In addition, some small-scale plants have been constructed using LFR in Australia, USA and Spain with output capacity ranging between 1.4 and 30 MW [39,40,42,43].

Other countries that are active in this field are Iran [44], Italy [45], Israel, United Arab Emirates (Shams 1, 100 MW PTC installed, phases 2 and 3 under feasibility study), India and Saudi Arabia [39].

7. Conclusion, remarks and summary of the key points

Solar thermal energy has considerable capability to contribute towards renewable energy future and carbon mitigation targets.

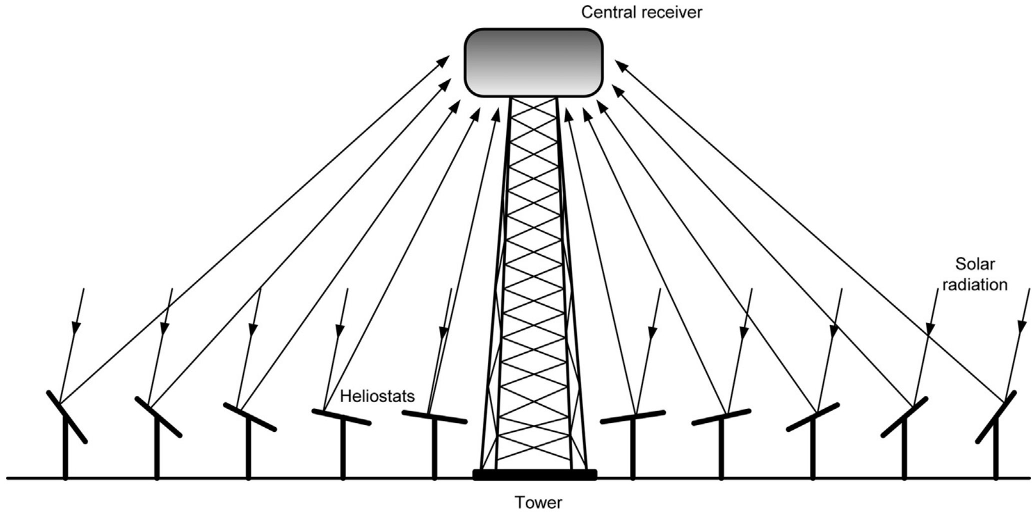

Fig. 13. Schematic of HFC system.

Table 2
Key features of solarthermal collectors in the context of PCC integration [24].

Collector technology		FPC	ETC	CPC	PTC	LFR	PDR	HFC
Concentrating technology		–	–	–	✓	✓	✓	✓
Non-concentrating technology		✓	✓	✓	–	–	–	–
Efficiency range		Low	Low	Low	Mid	Mid	High	High
Temperature (°C)		up to 100	up to 200	300	350–400	250–500	> 1500	> 1500
Industrial process heat [28,30]	Air and water systems	✓	✓	✓	–	–	–	–
	Steam generation	–	–	–	✓	✓	–	–
Solarthermal power production		–	–	–	✓	–	✓	✓
Potential for solar-assisted PCC (supply of reboiler duty)		–	✓	✓	✓	✓	–	–
Potential for solar-assisted PCC (supply of reboiler duty and auxiliary loads)		–	–	–	✓	✓	–	–

Integrated in a PCC-retrofitted power plant regardless of the connection point in the super structure (solar plant could be connected to PCC and/or power plant), a solar thermal energy and/or solar power production plant partially or totally could compensate the power plant output penalty from PCC solvent regeneration and/or PCC auxiliary loads.

The idea of integration of solar energy in PCC-retrofitted power plants is very new. Thus far, the number of researches available investigating various aspects of the technology found to be limited and not very comprehensive. This highlights the great potential existing in this field for further development, keeping in view the great possibility of its successful contribution in overcoming the energy intensive issues with PCC as well as its promising potential in increasing the share of renewable energy in existing power production plants.

The focus of most researches available in this field was found to be on compensating the PCC power plant penalty resulted from the turbine circuit steam bled for PCC solvent reboiler duty and two main concepts were proposed in the literature for this purpose. The first and most-studied concept is directly providing the duty of reboiler by solar thermal collection system instead of steam extraction. The major challenge in this field is the large solar installation cost; to provide the high amount of heat duty required for solvent regeneration, a reasonably high efficiency solar field with large aperture area would be required to be used. This has made the researchers divert their focus from total compensation of the reboiler duty to provide a fraction of it by solar thermal energy in order to reduce the capital cost requirement.

Currently in Australian context, the solar-assisted PCC technology in which the solar thermal energy is not used for direct power production is not eligible for renewable energy certificates. However, the considerable potential of its engagement in large solar energy fields installation and most importantly the promising contribution of such systems in carbon mitigation may attract the policy decision makers to reconsider its eligibility.

The other trend is solar repowering of high-pressure side feed water preheaters of the power plant, so the extra power produced by recovered high quality steam would make up the power plant output penalty due to low quality steam used for reboiler.

Hybridization of a conventional power plant retrofitted with PCC with solar thermal energy can reduce the energy penalty. The utilization of solar installation is more efficient compared to the concept of direct connection of solar field to the reboiler as; in cases when PCC is not operating, the solar thermal plant could be still used in power production and therefore producing more electricity from the same amount of fossil fuel without any added carbon emission. Solar repowering of PCC-retrofitted power plants was reported to offer better potential to provide total power penalty resulted from the reboiler duty with smaller size solar aperture installation. What is more, the solar repowering option has better chance of eligibility for LGC incentive as the solar thermal energy is used to produce power. Such hybridization carries high merit to gradually evolve renewable electricity production, because this exploits the use of existing industrial facility of fossil-fuelled power plants and workforce rather than utilizing large capital in new standalone solar to electricity power plants. Power plant hosting locations with high insolation potential and high ambient temperature are ideal candidates for such process integration.

The power requirements of the PCC auxiliary units (CO_2 compression trains, pumps and other minor equipment) imposes additional parasitic load on power plant output which were almost often overlooked by most literature and almost no system is proposed to compensate the resulted penalty.

Table 3
Summary of current research trends in integration of solarthermal energy with PCC-retrofitted power plants- key features.

Solar integration strategy	Connection point of solar plant to PCC-retrofitted power plant	Solar production mode	Reference	Key features of each study
			Wibberley et al.	• Proposed lean and reach solvent storage system • Presented different possibilities to integrate thermal energy in solar assisted PCC.
			Cohen et al.	• A preliminary feasibility study. • Solar field size proposed is more than 2 km^2. • Stated that collector field price of $100/$m^2$ or less is required for feasible solar integration.
Solar assisted PCC Supply of reboiler duty by means of direct connection of solar field or solar steam generator to PCC reboiler.	PCC reboiler	Thermal energy	Mokhtar et al.	• A study on net annual benefit of solar assisted PCC varying the electricity and carbon price and solar fraction for $100–600/$m^2$ price ranged solar collectors. • Showed that only 22% or less of reboiler duty could be feasibly provided by solar field. • Reported that collector cost of $100/$m^2$ or less and carbon price of $100/tonne makes the installation feasible. • Increased electricity price (to $0.1/kWh) with carbon price of $0.05/kg CO_2, makes installation of $300/$m^2$ collector fields economically justified. • Used LFR technology due to lower price. • Used concrete storage (max FLH=15). • Used an on/off control scheme for solar energy supply to reboiler which is not optimized. • Partial supply of reboiler duty would be more feasible.
Solar assisted PCC Supply of reboiler duty by means of direct connection of solar field or solar steam generator to PCC reboiler.	PCC reboiler	Thermal energy	Qadir et al.	• Techno economic study of solar assisted PCC technology in three locations in Australia. • Investigated the application of a range of concentrating and non-concentrating collectors. • ETC performed best when power, PCC and solar plants are heat integrated. • PTC performed best when there is no heat integration. • The net revenue is higher when the plants are highly integrated through heat exchanger network. • Without intensives, solar assisted PCC is not feasible in any of the investigated locations. • Investigated the effects of different incentives. • Carbon price of $44/tonne-$CO_2$ and more is required for positive revenue for solar assisted PCC technology with solar share of 0.2 in Sydney and Townsville. • If granted with LGC, a solar fraction greater than 0.8 is economically justified (Townsville has the best potential). • Melbourne did not show promising potential in any case. • Solar assisted PCC technology is not eligible for large scale renewable energy generation certificate in current Australian context.
Solar assisted PCC Supply of reboiler duty by means of direct connection of solar field or solar steam generator to PCC reboiler.	PCC reboiler	Thermal energy	Li et al.	• A feasibility study on solar assisted PCC in three locations in the world, investigating application of PTC and ETC. • Used phase change material for thermal storage. • The economic model investigating the cost of electricity and cost of avoidance of CO_2. • Analysed the solar assisted PCC economically based on variable solar collector price, phase change material (PCM) price and carbon dioxide recovery ratio. • Reported that the price of ETC to be less than $90/$m^2$ and PTC lower than $150/$m^2$ would be required for a feasible solar assisted PCC installation. • Alice spring in Australia showed the most potential for feasible installation of solar assisted PCC technology.

Table 3 (*continued*)

Solar integration strategy	Connection point of solar plant to PCC-retrofitted power plant	Solar production mode	Reference	Key features of each study
Solar assisted power plant Compensation of power plant output penalty by means of replacing high pressure steam used for power plant high-pressure side feed water preheaters by solar thermal energy	Power plant high-pressure side feed water preheaters	Thermal energy	Zhao et al.	• A very preliminary assessment of solar repowering of a PCC-retrofitted power plant. • The basis of the analysis is not provided in details. • Reported that if 100% of high pressure side feed water preheater is supplied by solar energy, the resulted power produced could potentially offset 100% of reboiler duty penalty. • Proposed a very complex control based on the assumption of turbine circuit being capable of adjusting to fast changes in steam flow rate. • Did not consider any thermal storage system to buffer the solar energy fluctuations. • Reported 17.2% improvement e.g. reduction in power plant output penalty. • Stated a reduction of about 58% per tonne of CO2 in annual solar cost compared to solar assisted PCC technology. • Did not investigate the effect of repowering on power plant original turbine circuit operation.
Supply of reboiler duty and PCC auxiliary loads	Solar thermal and/or power supply lines connected to PCC and/or power plant	Thermal and/or power	Parvareh et al.	• The objective was to provide both PCC auxiliary loads and reboiler duty from solar source. • Proposed different configuration possible to integrate the solar thermal and or power with PCC-retrofitted power plants. • Used PTC solar collector technology to produce power and/or thermal energy. • Reported promising potential to supply 100% penalty resulted from both reboiler duty and auxiliary loads operation. • Proposed the application of thermal storage in repowering configuration, arguing the existing power plants might not be capable of rapid adjustment to the frequent changes in steam extraction flow rate.

The trends from literature have shown that concentrated solar power and/or thermal energy systems could be efficiently used to potentially maintain the power plant original power output during PCC operation. This was shown to be possible through providing of both PCC auxiliary power load and solvent regeneration thermal energy requirements from a solar thermal and/or power plant. Possible configurations reviewed included parallel electricity generation, combined steam and solar electricity generation and solar repowering of the power plant. However, a clear-cut comparison between each of the possible solar power and/or solarthermal system configurations was not available in the literature. Such comparative analysis is best executed within a techno-economic framework considering each configuration's potential improvement to the power plant output.

Several solar thermal collector technologies were reviewed in context of their capability to be used for solar augmentation of PCC-retrofitted power plants. Low-temperature, low-efficiency and low-cost solar thermal collectors seem to have notable potential to be seamlessly implemented with PCC technology to provide solvent regeneration thermal energy, directly to the reboiler, specifically if optimally designed for temperature requirements. However, their potential for such implementation should be investigated in regards to their performance efficiency, environmental impact management issues and capital installation cost. Mid-temperature and mid-efficiency solar thermal collectors like parabolic trough collectors can be effectively used for plant repowering and carbon capture technology (both reboiler duty and auxiliary power requirement of PCC) in virtue of their mature technology and suitable temperature and efficiency range. High performance solar thermal technologies can supply the required energy by smaller area, and are able to be used to provide PCC auxiliary load as well as reboiler duty. However, the high overall operating and capital costs of these technologies make them unfeasible to be used in such an application. These technologies are still under research and commercial development. It might be more efficient if these types of solar technologies are used for direct electricity generation rather than in regaining power plant output penalty due to PCC operation. It is also found in some research works that process optimization and heat integration of the subsystems of the super structure (power plant + PCC + solar plant) will increase the viability of the solar integration.

Currently, the two-tank molten salt thermal storage system is the most accessible thermal storage technology to be used in solar thermal and/or power plants, in virtue of its thermal stability, low vapour pressure, low viscosity, high thermal conductivity and non-flammability. However, the large scale of thermal energy required for solar integration (thermal energy required for either of reboiler or high-pressure feed water preheaters) would result in larger thermal storage and considerably higher total solar capital cost. This intensifies the existing uncertainty about the feasibility of such solar integrations. This issue emphasizes the value of ongoing research on alternative storage systems for solar assisted PCC technology concept, in which solar energy is used in reboiler and lean and rich solvents are stored in number of storage tanks and would be dispatched to the stripper or absorber based on demand.

Despite great environmental and energy saving potentials, implementation of solar technology for carbon capture was found not to be feasible in most locations globally. This requires very low solar

thermal collection price, very effective incentive measures and funding to be considered economically feasible. Besides, a combination of local and climatic parameters like electricity prices, carbon taxes, financing conditions, cost of equipment and plant lifetime are important factors that significantly influence the viability of the technology. A number of statistic values for each intensive measure, the unit price of solar collector, electricity and carbon price required for a feasible solar integration as well as the percentage of improvement made to the power plant penalty are available in the reviewed literature. These data provide a good perspective of the status of the technology and the future directions of the research in the field. A summary of such literature trends and key statistic data provided in each work is presented in Table 3.

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